# Drying kinetics of osmotically pretreated carrot shreds to be used for preparation of sweet meat

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**Abstract:** The carrot shreds having 2 mm and 4 mm thickness were osmotically pre-treated with different proportions of powdered sucrose and were convectively dehydrated at different temperatures (50, 60 and 70 °C) up to a final moisture content of 4-5% (dry basis). The convective dehydration mechanism was well represented by Approximate Diffusion Model. During convective dehydration, the effective moisture diffusivity varied from $1.827 \times 10^{-9}$ m$^2$/sec to $4.587 \times 10^{-9}$ m$^2$/sec for shred size 2 mm and $1.832 \times 10^{-9}$ m$^2$/sec to $4.157 \times 10^{-9}$ m$^2$/sec for shred size 4 mm for the temperature range of 50 to 70 °C. The activation energy values ranged from 12.71 to 21.85 KJ/mole for shreds having 2 mm size; and 7.433 to 8.391 KJ/mole for shreds having 4 mm size. The dehydrated carrot shreds were packaged in aluminium laminates of thickness 42 micron and stored at ambient temperatures. The dehydrated shreds were utilized for the preparation of dairy based product named ‘gajrella’ or sweet meat. The gajrella prepared with carrot shreds treated with 35 g sucrose per 100 g carrot shreds dried at 70 °C has scored highest during sensory analysis.
**Keywords:** carrot shreds, convective dehydration, drying kinetics, effective moisture diffusivity, activation energy

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## 1 Introduction

**Carrot (*Daucus carota L.*)** a root vegetable, is popular and common among the vegetables in world due to its high nutritive value and is rather inexpensive. The carrot has been called the poor man’s ginseng as it contains more than 490 phytochemicals. It contains appreciable amount of vitamins $B_1$, $B_2$, $B_6$ and $B_{12}$ besides being rich in ß-carotene (Manjunatha, Mohan Kumar and Das Gupta, 2003). Beta-carotene is one of the most antioxidants in the carrot, and helps the immune system to target and destroy cancer cells in the body. It also prevents DNA variation and fat oxidation, and protects cells against free radicals. Further, vitamin A is an antioxidant which is key to the growth and repair of tissues and helps the body to fight with infections, keeps eyes healthy, nourishes epithelial tissues in the lungs, as well as of the skin. Carrots are also high in dietary fiber, which cannot be absorbed by the body and therefore, have no calorific value. However, the health benefits of eating fiber rich diet are immense including prevention of constipation, regulation of blood sugar, protection against heart diseases, reducing high

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levels of cholesterol and prevention of certain forms of cancers (Sharma et al., 2012 ). Carrots also contain a significant supply of calcium, potassium and phosphorus and are a good source of energy because they contain a lot of sucrose. This low cost crop could be converted to value added products, if processed properly.

A substantial quantity of harvests is lost in each season because of inadequate means of preservation. Higher productions in peak season cause a glut in the market and the growers have no alternative but to sell this valuable crop at very low price. The different methods for preservation include low temperature storage, controlled atmosphere storage (CAS) and modified atmospheric packaging (MAP) but these methods are generally for high valued cash crops. The best alternative is to dehydrate the crop to a moisture content at which it becomes shelf stable. Drying can constitute an efficient solution of preservation to these problems. The wide variety of dehydrated foods, which today are available to the consumer are in form of snacks, dry mixes and soups, dried fruits etc. (Krokida et al., 2003).

Dehydration offers highly effective and practical means of preserving fruits and vegetables and leads to reduced post harvest losses in addition to abating shortages in supply. It is a complex operation involving heat and mass transfer (Doymaz, 2004; Ertekin and Yaldiz, 2004) which may cause changes in product quality. Drying characteristics of specific products should be determined to improve its quality.

Carrot based condensed milk product (gajrella) is a source of concentrated nutrients and is prepared by cooking carrot shreds in milk with sucrose and moderately frying in hydrogenated oil (Basantpure, Kumbhar and Awashthi, 2003). Gazrella is perishable and can be stored for 2-3 days at room temperature as sourness, drying up and rancidity development decrease the shelf life. It will be more useful if the raw material (i.e. carrot shreds) of this product is preserved. The shelf life of carrot shreds can however, be increased by either osmotic or convective dehydration or a combination of both. The dehydrated carrot shreds can allow the consumer to enjoy the sweet meat gajrella during off season.

A number of researchers have studied the dehydration behavior of carrot slices, cubes, osmosed carrot cubes, shreds and carrot pomace. Osmotic pre-treatment of carrot shreds with 50° Brix solution before dehydration leads to a substantial loss in moisture content and hence reduction in drying time (Singh, 2001). Doymaz (2004) studied the convective drying characteristics of carrot cubes and revealed that effective moisture diffusivity increased with increase in temperature.

The objective of the present study was to determine experimentally the thin-layer drying kinetics of osmotically pre-treated carrot shreds and their subsequent utilization for the preparation of sweet meat during the off season.

## 2 Materials and methods

Fresh carrots of local red variety were procured from the local market of Longowal (Sangrur), Punjab. The carrots were washed, trimmed and manually peeled and again washed to remove adhered peels on the surface. The washed carrots were shredded into two different sizes of 2 mm and 4 mm thickness by a manual grater. The sizes of the shreds were selected to see the effect of shred thickness on quality of gajrella. No blanching was done prior to pre-treatment with sucrose as it has been reported detrimental to osmotic dehydration process due to loss of semi-permeability of cell membrane (Ponting, 1973) and reduction of beta-carotene of carrots (Bao and Chang, 1994; Kalra, 1990). The carrot shreds without sucrose powder were the control sample. The powdered sucrose was added to the shreds at the rate of 25 g, 35 g and 45 g per 100 g of carrot shreds. Purpose of addition of sugar was that sucrose has preservative effect on the color of shreds and other quality attributes like flavour and nutritional value. Osmotic dehydration inhibits the action of polyphenol oxidase and retards the loss of volatile flavour constituents during dehydration (Ponting, 1973).

**2.1 Convective dehydration**

Experimental drying unit for hot air drying used in this study was the laboratory scale batch type tray drier fabricated in the Department of Food Engineering and Technology, Sant Longowal Institute of Engineering and Technology, Longowal (Punjab) India. It was equipped with forced circulation of air having drying chamber, blower, electric heaters, temperature PID controller with sensor PT-100 and drying trays (Figure 1). The temperature range that can be regulated was between 40 to 100 °C. Drying air passed from the heater according to desired flow direction (over or through the product) controlled by opening the desired exhaust port.

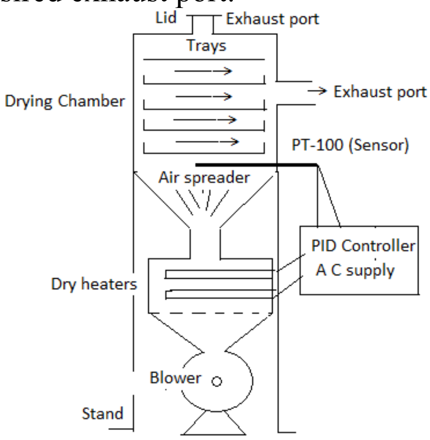


Figure 1 Schematic diagram of laboratory dryer

The osmotically pre-treated carrot shreds were convectively dried in thin layer at temperatures of 50 °C, 60 °C and 70 °C (Doymaz, 2004) with direction of airflow over the product in blind aluminium trays up to moisture content of 4-5% (dry basis) with the air velocity 1.5 m/s (Krokida et al., 2003). The air velocity was measured at the exhaust port of the dryer using a Vane type digital anemometer (Lutron Anemometer, Taiwan). The obtained data was subsequently utilized in the determination of moisture content, moisture ratio, and effective moisture diffusivity and activation energy. Moisture content of the carrot shreds was determined by using an air oven at 102 °C until reaching constant weight in consecutive readings taken after 30 minutes (Ertekin and Yaldiz, 2004; Koyuncu, Yunus and Lule, 2007).

**2.2 Validation of convective drying models**

The various empirical drying models (Table 1) have been used to quantify thin layer convective drying kinetics of carrot shreds (Doymaz, 2007; Ertekin and Yaldiz, 2004; Premi *et al*. 2010; Singh, Panesar and Nanda, 2006). The moisture ratio was simplified to $M_t / M_o$ instead of $(M_t - M_e)/(M_o - M_e)$ due to long drying times (Doymaz, 2004; Ertekin and Yaldiz 2004; Singh, Panesar and Nanda, 2006). Where, $M_t$ is the moisture content at time t, $M_o$ is the initial moisture content and $M_e$ is the equilibrium moisture content (dry basis).

**Table 1 Selected drying models for describing drying behavior of carrot shreds (without sucrose) and sucrose pre-treated carrot shreds**

| Model Name | Model Equation |
|---|---|
| Newton (Lewis) model | MR = exp (-k t) |
| Page model | MR = exp (-k $t^n$) |
| Wang and Singh | MR = 1 + at + $bt^2$ |
| Logarithmic | MR = a exp (-kt) + c |
| Two-term exponential | MR = a exp (-kt) + (1-a) exp (-kat) |
| Henderson and Pabis (GEM) | MR = a exp (-kt) |
| Verma *et. al* | MR = a exp (-kt) + (1-a) exp (-gt) |
| Modified Henderson and Pabis | MR= a exp (-kt) + b exp (-gt) +c exp (-ht) |
| Logistic Model | MR=b/ (1+a exp (kt)) |
| Two term model | MR= a exp (-kt) + b exp (-$k_1$t) |
| Approximate diffusion model | MR =a exp (-kt) + (1-a) exp (-kbt) |

**2.3 Statistical analysis and adequacy of fit of empirical models**

The non-linear least square regression analysis based on Levenberg-Morquardt algorithm was used to estimate the parameters of the models by fitting the model equations to experimental data by the software Statistica, 7.0 (Table 1). The coefficient of determination ($R^2$), reduced chi-square ($\chi^2$) (Equation 1), and the root mean square error (RMSE) (Equation 2) were used as criteria for verifying the goodness of fit. These parameters are not a good criterion for evaluating non-linear mathematical models, because RMSE and chi square compare the differences between the predicted moisture ratios to the experimental moisture ratios, the percent mean relative deviation modulus (E%) (Equation 3) was also used to select the best equation to account for variation in the drying curves (Ertekin and Yaldiz, 2004). The relative percent error compares the absolute differences between the predicted moisture contents with the experimental moisture contents throughout drying. Therefore, the best model was chosen as one with the highest coefficient of correlation ($R^2$), and the least $\chi^2$, RMSE and mean relative deviation modulus (E).

$$\chi^2 = \frac{\sum_{i=1}^{N} (\text{experimental value} - \text{predicted value})^2}{N - n} \tag{1}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (\text{experimental value} - \text{predicted value})^2}{N}} \tag{2}$$

$$E(\%) = \frac{100}{N} \sum_{i=1}^{N} \left| \frac{\text{Experimental Value} - \text{predicted value}}{\text{Experimental value}} \right| \tag{3}$$

The values of E less than 5.0 indicate an excellent fit, while values greater than 10 are indicative of a poor fit (Lomauro, Bakshi and Labuza, 1985; Gencturk et al., 1986). In Equations (1), (2) and (3), N and n are the number of observations and number of unknown constants in the model equation, respectively.

## 2.4 Estimation of average moisture diffusivities

The basic equation of Fick's unsteady state law of diffusion is of the form given in Equation (4)

$$\frac{\partial M}{\partial T} = D\frac{\partial^2 M}{\partial r^2} \tag{4}$$

The carrot shreds were dried in form of slabs having size 15 cm × 15 cm with thickness of slab 1.5 cm. For Fick's diffusion equation, the analytical solution for slab geometry assuming that (i) the moisture is initially uniformly distributed throughout the sample, (ii) mass transfer is unidirectional, (iii) surface moisture content of the samples instantaneously reaches equilibrium with the conditions of the surrounding air, and (iv) assuming that the sample size and geometry remain constant during convective drying is as below in Equation (5) (Crank, 1975)

$$MR = \frac{8}{\pi^2}\sum_{i=1}^{\infty}\frac{1}{(2i-1)^2}\exp\left[\frac{(2i-1)^2\pi^2 D_{eff}\,t}{4L^2}\right] \tag{5}$$

Where $D_{eff}$ is the effective diffusivity ($m^2$/sec), L is half-slab thickness (m) and i is positive integer and represent the number of terms of the series. This equation can be simplified by taking the first term of Equation (5), assuming that the effect of terms other than first one on value of diffusivity was non-significant (Doymaz, 2004; Margaris and Ghiaus, 2007; Singh and Gupta, 2007) Equation (6).

$$MR = \frac{M - M_e}{M - M_o} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}}{4L^2}t\right) \tag{6}$$

The effective moisture diffusivity was calculated at different intervals of time. The average effective moisture diffusivity was calculated by Equation (7).

$$\left(D_{eff}\right)_{avg} = \frac{\sum_{i=1}^{N} D_{eff(i)}}{N} \tag{7}$$

Where, N represents the total number of data points.

## 2.5 Estimation of activation energy

The dependence of average effective moisture diffusivity $(D_{eff})_{avg}$ on drying air temperature was obtained by Arrhenius relation (Doymaz, 2004; Singh and Gupta 2007) (Equation (8)).

$$D_{eff(avg)} = D_o \exp\left[\frac{-E_a}{R\,(T + 273)}\right] \tag{8}$$

Where T is the temperature (°C); R is the universal gas constant having a constant value of 8.314 kJ/mole K; $D_o$ is the effective moisture diffusivity at 0 °C (273 K) temperature; and $E_a$ is the activation energy. Activation energy was calculated from the negative slope of straight line between $\left(\frac{1}{T+273}\right)$ and $\log_e\left(\left(D_{eff}\right)_{avg}\right)$. Thermodynamically, activation energy is the relative ease with which the water molecules pass the energy hurdle when migrating within the product.

## 3 Results and discussion

### 3.1 Effect of addition of varying sucrose proportions on dehydration kinetics

The total convective dehydration times of carrot shreds at 50, 60 and 70°C, when dried to a final moisture content of 4-5 % (d.b) are as given in Table 2. With increase in sucrose proportion, there is reduction in the total convective drying time. The total convective dehydration times for 4 mm size un-osmosed carrot shreds was 410 min and were 390, 380 and 370 min for 25 g, 35 g and 45 g sucrose powder per 100 g carrot shreds respectively at 50°C drying air temperature (Table 2). The reduction in drying time of 4 mm size carrot shreds was 4.88% for 25 g sucrose per 100 g carrot shreds, 7.32% for 35 g sucrose per 100 g carrot shreds and 9.76% for 45g of sucrose per 100g carrot shreds when compared with the time taken by carrot shreds sample with no sucrose powder at 50 °C drying air temperature.

**Table 2 Total convective drying time for carrot shreds.**

| Drying air Temp (°C) | Drying time in minutes | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Control (no sucrose) | | Osmotic Pre-treatment | | | | | |
| | | | 25 g Sucrose/100 g carrot shreds | | 35 g Sucrose/100 g carrot shreds | | 45 g sucrose/100 g carrot shreds | |
| | 2 mm | 4 mm | 2 mm | 4 mm | 2 mm | 4 mm | 2 mm | 4 mm |
| 50 | $500^a$ | $410^a$ | $360^a$ | $390^a$ | $350^a$ | $380^a$ | $340^a$ | $370^a$ |
| 60 | $360^b$ | $350^b$ | $320^b$ | $320^b$ | $310^b$ | $310^b$ | $300^b$ | $300^b$ |
| 70 | $340^{bc}$ | $300^c$ | $270^c$ | $280^c$ | $260^c$ | $270^c$ | $240^c$ | $260^c$ |

Note: Mean values followed by different letters in a same column are significant different at $p < 0.05$

Similarly, reduction in convective dehydration time with sucrose addition in 2 mm shred size is 28% for 25 g sucrose per 100 g shreds, 30% for 35 g sucrose per 100 g shreds and 32% for 45 g sucrose per 100 g carrot shreds when compared to time taken for control sample dehydrated at 50 °C temperature. The reduction in total convective dehydration time with increase in sucrose proportion may be due to lowering of initial moisture content by the addition of sucrose. Further, the sucrose treated carrots shreds can be dried to slightly higher moisture to achieve a similar water activity compared to the dried fresh carrot shreds. Also, the addition of powdered sucrose resulted in the oozing out of water from carrot shreds to the surface due to osmosis, which helped in easier surface moisture removal at initial time of drying. The reduction in drying times in sugar treated blue berries in comparison to fresh blue berries has been reported by Shi et al.

(2008). Singh (2001) has also reported shortening of convective dehydration time of carrot shreds due to osmotic pre-treatment. Amami et al. (2008), Matusek and Meresz (2002) for carrots; Ibitwar et al. (2008) for plums; Torringa et al. (2001) for mushrooms have also reported that osmotic dehydration spectacularly shortened the total convective drying time.

Among the sucrose powder added carrot shreds, minimum drying time was taken by the carrot shreds pre-treated with 45 g sucrose powder per 100 g of carrot shreds for both shreds of 2 mm and 4 mm size. This may be due to less initial moisture and greater osmotic effect due to high sucrose level. Drying behavior of carrot shreds of 4 mm at 50 °C is shown in Figure 2. Rapid drying takes place initially and after that there is slow drying. The drying behavior was similar for higher drying air temperatures (60 °C and 70 °C) except the differences of increased drying rates and reduced total convective drying times.

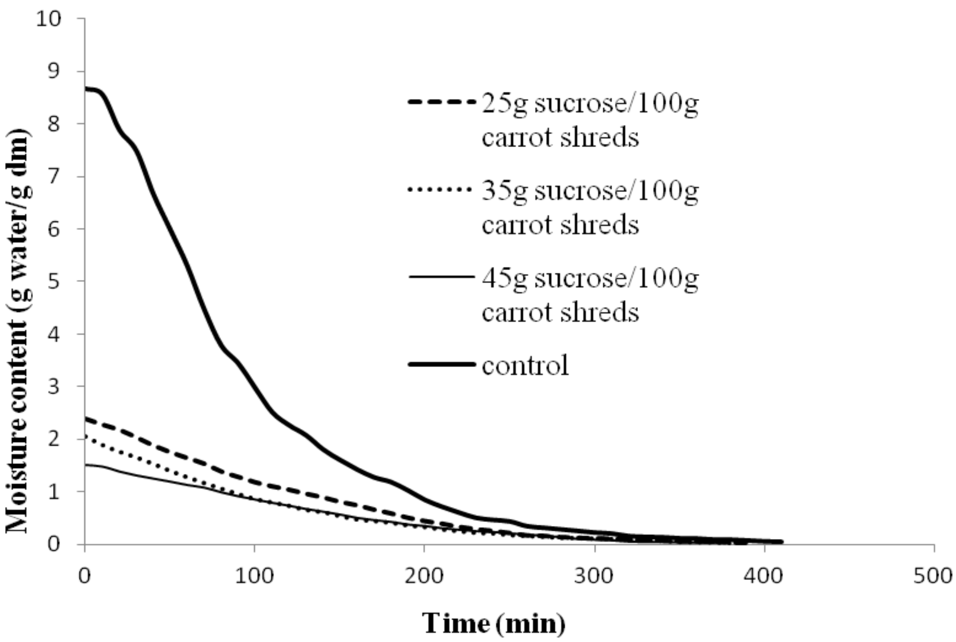


Figure 2 Effect of sucrose powder proportions on convective drying kinetics of carrot shreds of size 4 mm and at 50 °C drying air temperature

The drying rate versus moisture content (dry basis) curve at temperature 50 °C of shred size 4 mm shows that carrot shreds without sucrose powder has the highest drying rate as compared to the osmotically pre-treated carrot shreds (Figure 3). The drying rates of the untreated carrot shreds were high due their high initial moisture content. The drying rates were higher in the beginning of the drying process followed by decrease in drying rates with decrease in moisture content of sample for all carrot shreds samples. The reduction in drying rate with progression of drying may be attributed to the inhibition of moisture diffusion by sucrose infused to the shreds. The reduction in drying rates might be due to the reduction in porosity of the material due to shrinkage with advancement of drying process, and this shrinkage increased the resistance to movement of water leading to further fall in drying rates (Singh and Gupta, 2007).

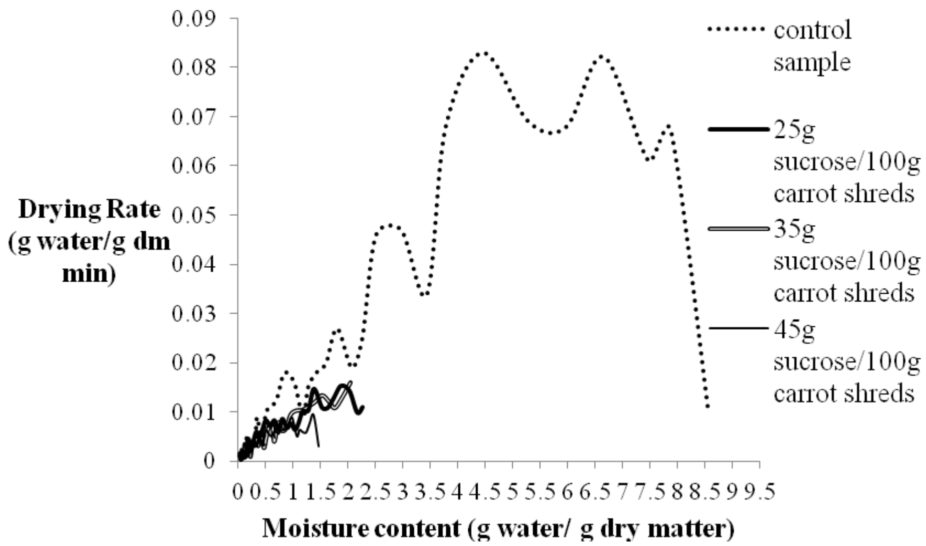


Figure 3 Drying rate curve for various proportions of sucrose powder added to carrot shreds of 4 mm size at drying air temperature of 50 °C

### 3.2 Effect of drying air temperature on convective drying kinetics

With increase in drying air temperature from 50 °C to 70 °C the drying time for carrot shreds having 2 mm size has been reduced from 500 to 340 min for carrot shreds without sucrose powder and from 360 to 270 min, 350 to 260 min and 340 to 240 min for carrot shreds treated with 25g, 35g and 45g of sucrose powder per 100 g of carrot shreds, respectively. The decrease in drying time was 32% for untreated carrot shreds and 25, 25.7 and 29.41% respectively for 25 g, 35 g and 45 g of sucrose per 100 g of carrot shreds of size 2 mm when temperature was increased from 50 to 70 °C. The reduction in drying time with increase of drying air temperature is due to the fact that high temperature provides more heating energy which speeds up the movement of water molecules (Maskan, Kaya and Maskan, 2002). The higher temperatures also provide a larger water vapor pressure deficit (the difference between the saturated water vapor pressure and partial pressure of water vapor in air at a given temperature), which is one of the driving forces for outward moisture diffusion process (Prabhanjan, Ramaswamy and Raghavan, 1995). Similar behavior of decrease in drying time with increase of drying air temperature were obtained by Doymaz (2004) for carrot cubes; Krokida et al. (2003) for drying of vegetables like carrot, spinach, pumpkin, celery etc. and Shi et al. (2008) for fresh blue berries. Figure 4 shows the drying behavior of carrot shreds with increase in temperature.

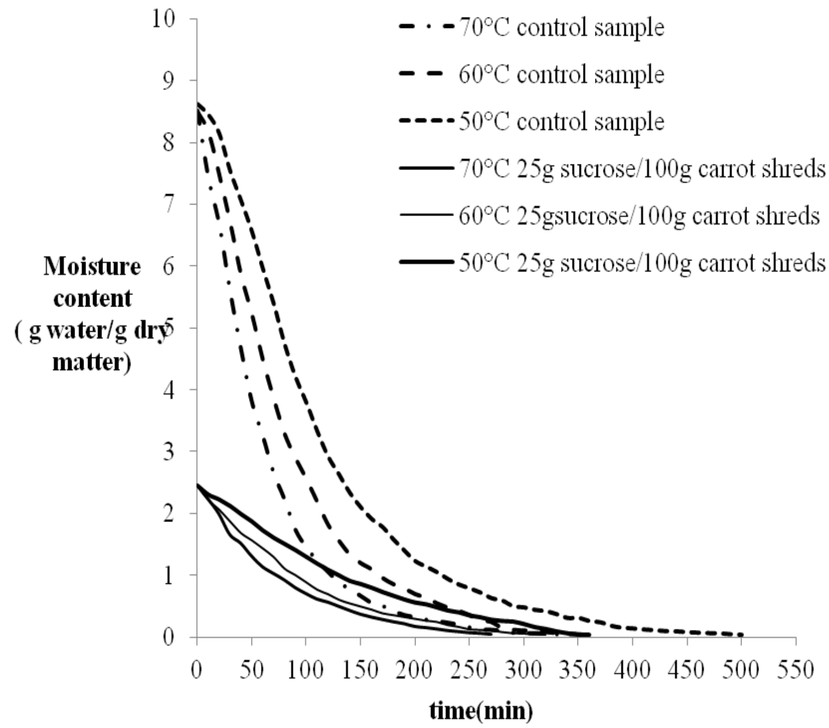


Figure 4 Effect of drying air temperature on drying kinetics of carrot shreds (2 mm size)

The drying rates were highest for 70 °C followed by 60 and 50 °C for all samples of carrot shreds (Figure 5). The drying rates were higher in beginning of the process for all samples which could be attributed to increased evaporation of water at surface. The rate drying then declined with reduction in moisture content as less free water is available on the surface and drying rate is dominated by moisture diffusion from inwards to surface. Also, the drying curve indicated that the drying process occurred mainly in falling rate period. Non-existence of a constant rate period may be explained by the fact that surface of product dries out very quickly and a partial barrier is generated to resist moisture movement freely. Maskan, Kaya and Maskan (2002) for drying of pestil leather and Shi et al. (2008) for infra-red drying of blue berries also reported presence of falling rate period.

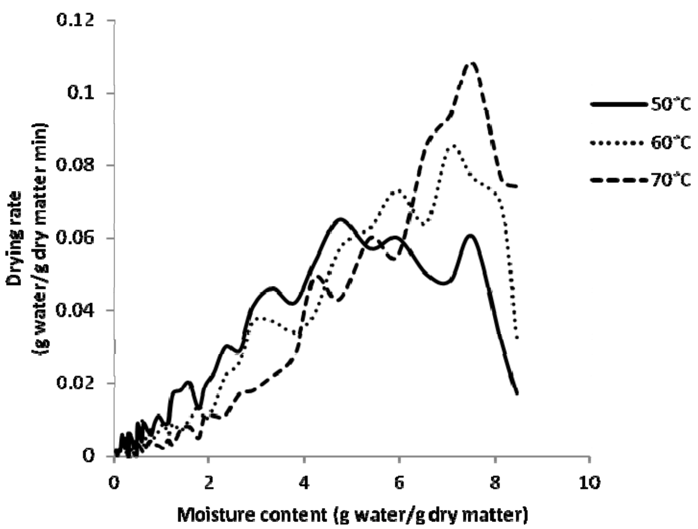


Figure 5 Effect of drying air temperature on drying rate of carrot shreds (2 mm) with no sucrose powder

Kaleemullah, Kailappan and Varadharaju (2002), Andres et al. (2007), Singh and Gupta (2007) have reported the increase in convective dehydration time due to osmotic pre-treatment due to the resistance offered to water removal by solute gained during osmotic pre-treatment. The deviation of results in the present study might be due to the lesser moisture binding effect of sucrose in 2 to 4 mm sized carrot shreds as compared by sample size used by the other researchers.

### 3.3 Effect of shred size on dehydration

In case of control samples of carrot shreds (i.e. without sucrose addition), the higher drying time was taken by carrot shred size of 2 mm than carrot shred size of 4 mm; whereas, the drying time taken by 2 mm thick carrot shreds was less in comparison to 4 mm thick carrot shreds treated with 25 g, 35 g and 45 g sucrose per 100 g of carrot shreds. This may be due to rapid evaporation of oozed out water which was more in case of 2 mm size shreds in comparison to 4 mm sized carrot shreds. The oozing out of more water was due to the reason that sucrose acted on increased surface area in case of 2 mm carrot shreds. Figure 6 shows the effect of size on drying time and drying behavior during convective dehydration.

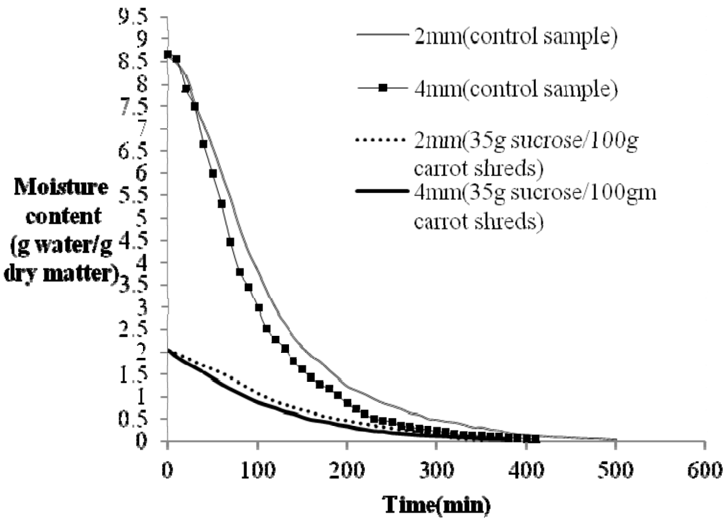


Figure 6 Effect of carrot shred size on drying time dried at air temperature 50 °C

### 3.4 Validity of various empirical models for convective drying kinetics

The highest values of $R^2$ and lowest values of $\chi^2$, RMSE and E% were obtained with the approximate diffusion model followed by logarithmic model. Therefore, this model can be considered to represent the drying behavior of carrot shreds in a convective type dryer. The values of constants for best fitted model for 2 mm size carrot shreds are given in Table 3.

**Table 3 Regression coefficients and statistical parameters for approximate diffusion model for shred size 2 mm**

| Treatment | Temp (°C) | Model constants | | | Statistical parameters | | | |
|---|---|---|---|---|---|---|---|---|
| | | a | k | b | $R^2$ | $\chi^2$ | RMSE | E% |
| Control sample | 50 | -0.358 | 0.047 | 0.236 | 0.999 | $5.99\times10^{-5}$ | 0.008 | 6.189 |
| | 60 | -0.239 | 0.077 | 0.183 | 0.999 | $4.63\times10^{-5}$ | 0.007 | 13.490 |
| | 70 | -0.144 | 0.087 | 0.212 | 0.999 | $6.25\times10^{-5}$ | 0.008 | 18.210 |
| 25 g sucrose/100 g carrot shreds | 50 | -6.463 | 0.131 | 0.907 | 0.991 | $1.6\times10^{-4}$ | 0.012 | 20.010 |
| | 60 | -3.052 | 0.017 | 0.869 | 0.999 | $8.55\times10^{-5}$ | 0.009 | 10.370 |
| | 70 | -0.034 | 0.377 | 0.035 | 0.999 | $9.42\times10^{-5}$ | 0.009 | 11.060 |
| 35 g sucrose/ 100 g carrot shreds | 50 | -4.604 | 0.014 | 0.854 | 0.999 | $1.9\times10^{-4}$ | 0.013 | 16.330 |
| | 60 | -0.584 | 0.026 | 0.499 | 0.999 | $9.82\times10^{-5}$ | 0.009 | 7.665 |
| | 70 | -4.717 | 0.021 | 0.917 | 0.999 | $1.2\times10^{-4}$ | 0.010 | 12.300 |
| 45 g sucrose/100 g carrot shreds | 50 | -0.778 | 0.022 | 0.502 | 0.999 | $1.1\times10^{-4}$ | 0.009 | 7.148 |
| | 60 | -6.587 | 0.017 | 0.895 | 0.999 | $1.4\times10^{-4}$ | 0.011 | 10.370 |
| | 70 | -5.147 | 0.019 | 0.912 | 0.999 | $1.6\times10^{-4}$ | 0.011 | 11.770 |

Figure 7(a) and 7(b) shows the comparison of moisture ratio curves of experimental data with the predicted values of the best fitted model (approximate diffusion model) for control sample of carrot shreds and 25 g sucrose per 100 g carrot shreds of size 2 mm dried at 70 °C. In these graphs data points try to superimpose each other. The graphs also support the calculated values of best fit.

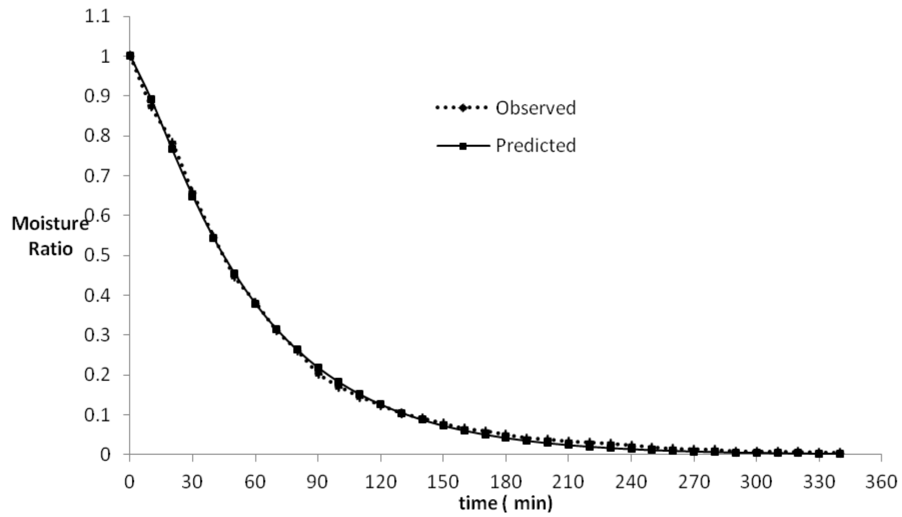


Figure 7(a) Comparison of moisture curves of observed and predicted (approximate diffusion model) for 70 °C temperature and control sample of carrot shreds of size 2 mm.

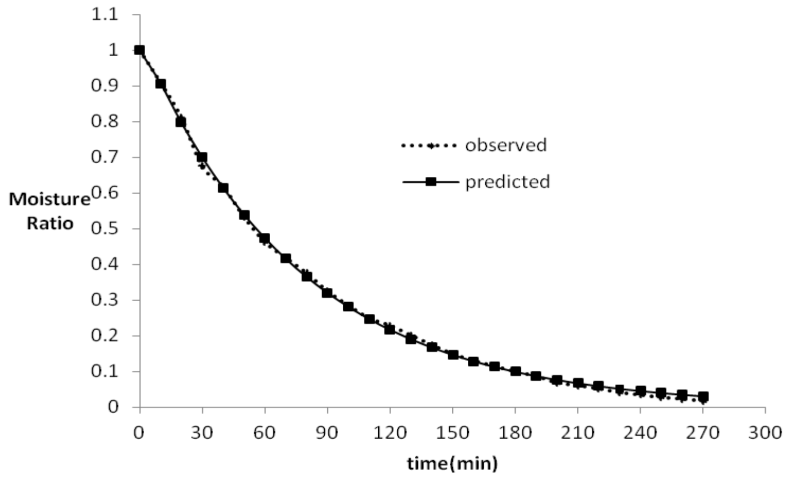


Figure 7(b) Comparison of moistureratio curves of observed and predicted (approximate diffusion model) for 70°C temperature and 25g sucrose/100g of carrot shreds of size 2 mm.

### 3.5 Effective moisture diffusivity for convective drying

The values of effective moisture diffusivity for all samples and drying conditions are presented in Table 4, which indicates that the drying air temperature has a pronounced influence on the value of effective diffusivity.

**Table 4 Effective diffusivity values ($m^2$/sec) for drying of carrot shred slabs ($D_{eff} \times 10^{-9}$)**

| Sucrose concentration | Temp.(°C) | Diffusivity ($m^2$/sec) ( $D_{eff} \times 10^{-9}$ ) | |
|---|---|---|---|
| | | Shred 2 mm | Shred 4 mm |
| Control sample | 50 | 2.546 | 3.093 |
| | 60 | 3.437 | 3.660 |
| | 70 | 4.588 | 4.157 |
| 25 g sucrose/100 g Carrot shreds | 50 | 1.856 | 2.155 |
| | 60 | 2.817 | 2.432 |
| | 70 | 3.341 | 2.757 |
| 35 g sucrose/100 g carrot shreds | 50 | 1.827 | 2.347 |
| | 60 | 2.637 | 2.628 |
| | 70 | 3.762 | 3.023 |
| 45 g sucrose/100 g carrot shreds | 50 | 1.995 | 1.833 |
| | 60 | 2.240 | 2.105 |
| | 70 | 3.122 | 2.420 |

Effective moisture diffusivity during convective dehydration increased with increase in drying temperature for all samples. The increase in effective moisture diffusivity with increase in drying air temperature might be due to increase of the vapor pressure in carrot shreds. Drying at 70 °C has the highest values of effective diffusivity and the lowest values were obtained for 60 °C and then for 50 °C (Figure 8). Shi et al. (2008) revealed that the high drying rate at high drying temperature could be due to more heating energy which speeds up the movement of water molecules and results in higher moisture diffusivity. The values for effective diffusivity ranged from $1.827 \times 10^{-9}$ to $4.587 \times 10^{-9}$ $m^2$/sec for shred size 2 mm and $1.832 \times 10^{-9}$ to $4.154 \times 10^{-9}$ $m^2$/sec for carrot shred size 4 mm for temperature range of 50 to 70 °C. These values are within the general range $10^{-9}$

to 10 $^{-11}$ $m^2$/sec for drying of food materials (Zogzas, Maroulis and Marinos-Kouris, 1996). The effective diffusivity values were 0.776 to 9.335 × $10^{-9}$ $m^2$/s for carrot cubes (Doymaz, 2004); 6.43 × $10^{-10}$ $m^2$/s for grape bed (Margaris and Ghiaus, 2007) and were 2.40 - 3.89 × $10^{-9}$ $m^2$/s for drying of drumstick leaves at temperatures 50 to 80°C (Premi et al., 2010).

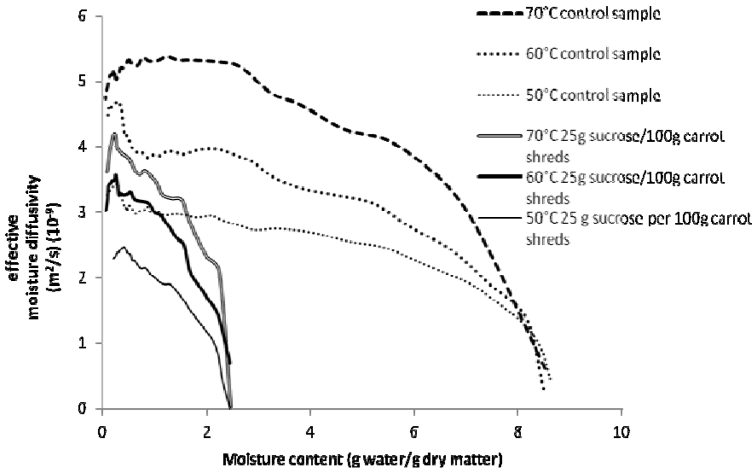


Figure 8 Effect of temperature and moisture content on effective moisture diffusivities of carrot shreds of size 2 mm convectively dried at 50°C.

Figure 8 shows that effective moisture diffusivity ($D_{eff}$) increased with decrease in the moisture content during convective dehydration of un-treated and sucrose treated carrot shreds. This behavior might be due to the fact that the effective moisture diffusivity depends up on moisture as well as temperature of the product. The diffusion coefficient decreases with decreasing moisture content, but is more dependent on product temperature than moisture content (Adu and Otten, 1996). At the later stages of drying, the temperature of the product will approach to the dry bulb temperature of the drying air, which would result in increased diffusivity. In the last phase, there is a sharp decrease of moisture diffusivity, although the product temperatures were high. This is due to less availability of moisture in the dried product (Singh and Gupta, 2007).

The anomalous behavior of effective diffusivity was observed with the increase in sucrose proportions of carrot shreds of both sizes. An increase in effective diffusivity values were found with 35 g sucrose addition per 100 g of carrot shreds for all temperatures for shred size 4 mm and for 70 °C for shred size 2 mm as compared to 25 and 45 g sucrose addition per 100g of carrot shreds. This anomalous behavior might be due to the two important effects on the moisture diffusivities in air drying viz. the binding forces between water and infused sucrose in pores and case hardening due to faster surface drying. The relative effect of these two effects will vary with addition of sucrose in different proportions. The infused sucrose act as water- binding agent and reduces the moisture diffusivity (Mauro and Rodrigues, 2005). The decrease in effective diffusivities of carrot shreds with 45 g sucrose addition per 100g carrot shreds was expected due to resistance imparted to internal moisture movement because of binding between water and sucrose. Park et al., 2002 also reported that the pears having high surface moisture can dry very fast, forming case hardening. Some case hardening in carrot shreds treated with lesser sucrose that is 25 g sucrose per 100 g shreds combined with binding forces effects due to sucrose could cause the water diffusivity decrease in comparison with carrot shreds with 35 g sucrose per 100 g carrot shreds. Similar trend of anomalous behavior in effective diffusivities was observed during the evaluation of influence of solute impregnation on effective diffusivities during air drying of fresh and osmotic treated apple tissue by Mauro and Rodrigues (2005); in which greater diffusivity values were observed for treatment of apple slices in 50% sucrose solution than treatment in 40 and 60 % sucrose solution, at all temperatures (50, 60, 70 and 80 °C). The high diffusivity in the samples with no sucrose might be due to high moisture (approximately 90% on wet basis) of sample.

Figure 9 shows that effective moisture diffusivity values were higher for control sample (without sugar) when compared with the sucrose treated carrot shreds of size 2 mm dried at temperature of 70 °C. The diffusivity values were lowest for carrot shreds having 45 g sucrose per 100 g of carrot shreds. This may be due to less availability of free moisture in sucrose treated shreds. With decrease in available free moisture, the effective diffusivity values first increased and then decreased in the end, as described before. Similar behaviors were obtained for temperatures 60 °C and 50 °C.

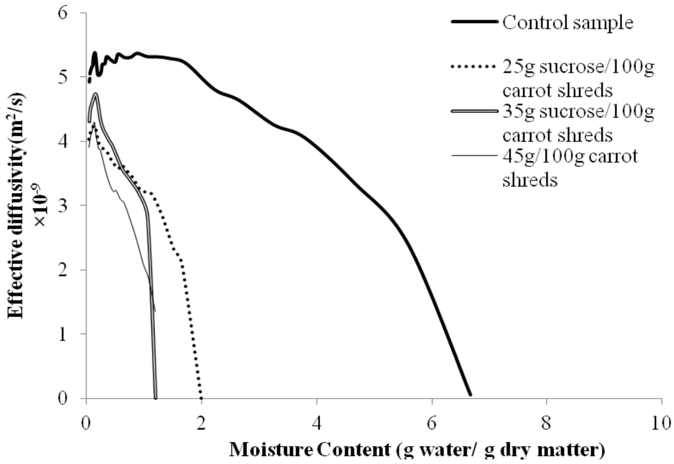


Figure 9 Effect of sucrose pre-treatment and moisture content on effective moisture diffusivities of carrot shreds of size 2 mm convectively dried at 70°C

### 3.6 Activation energy for convective drying kinetics

Activation energy values were higher for carrot shreds with sucrose proportion 35 g sucrose/100 g of carrot shreds size 4 mm and 45 g sucrose/100 g carrot shreds of size 2 mm when energy values of all samples were compared. For 2 mm shred size, the activation energy for control sample was 17.821 kJ/mol and for 4 mm size, the energy value for control sample was 8.169 kJ/mol. The increase in activation energies with increase in sucrose proportions for shred size 2 mm till sucrose proportion of 35 g of per 100 g carrot shreds was observed; whereas for carrot shreds having 4 mm size, a decrease in activation energy was observed till sucrose powder proportion 35 g/100 g of carrot shred and then there is an increase with further increase of sucrose to 45g/100g of carrot shreds. The variation in energy values may be due to the relative binding and osmosis effect of sucrose on both shred size. Singh and Gupta (2007) and Shi et al. (2008) have reported the higher activation energy for fresh samples as compared with osmotically pre-treated samples but in our study this was not observed. The activation energy values ranged from 12.71 to 21.85 KJ/mole for shred size 2 mm; and 7.433 to 8.391 kJ/mole for shred size 4 mm. These values are close to the activation energy values (15 - 40 kJ/mole) by Rizvi (1986) for various foods. The value of activation energy ranged from 10.3 to 21.7 kJ / mole for drying of pestil with varying slab thickness (Maskan, Kaya and Maskan, 2002). Shi et al. (2008) revealed that, the activation energy ($E_a$) of fresh blueberries was 66.3 kJ/mole, slightly higher than that for sugar-infused blueberries (61.2 kJ/mole). The values of activation energy for carrot shreds are given in Table 5.

**Table 5 Activation energy (KJ/mole) for carrot shreds (control and pre-osmosed sample)**

| Sucrose concentration | shred size 2 mm | | shred size 4 mm | |
|---|---|---|---|---|
| | Activation energy (KJ/mole) | $R^2$ | Activation energy (KJ/mole) | $R^2$ |
| control sample | 17.821 | 0.96 | 8.169 | 0.0099 |
| 25 g sucrose/100 g carrot shreds | 18.683 | 0.99 | 7.433 | 0.95 |
| 35 g sucrose/100 g carrot shreds | 21.855 | 0.959 | 7.553 | 0.927 |
| 45 g sucrose/100 g carrot shreds | 12.712 | 0.783 | 8.391 | 0.955 |

## 4 Conclusions

Drying of carrot shreds treated with different sucrose powder proportions at different drying air temperatures occurs in falling rate period. Drying time reduced with increase in temperature from 50 to 70 °C and with increase in sucrose concentration from no sucrose to 45 g sucrose per 100 g of carrot shreds. Approximate diffusion model was the best among the selected models for describing the drying behavior of shreds. The effective diffusivity values for convective drying of carrot shreds ranged from $1.827 \times 10^{-9}$ to $4.587 \times 10^{-9}$ $m^2$/sec for shred size 2 mm and $1.832 \times 10^{-9}$ to $4.15 \times 10^{-9}$ $m^2$/sec for carrot shred size 4 mm. Activation energy values ranged from 12.712 to 21.855 kJ/mole for carrot shreds 2 mm and 7.433 to 8.391 kJ/mol for carrot shreds of 4 mm. Dehydrated shreds were utilized for the preparation of sweet meat gajrella, a product prepared from heat desiccated milk and carrot shreds. The gajrella prepared with carrot shreds treated with 35 g sucrose per 100 g carrot shreds dried at 70 °C has scored highest during sensory analysis. The attributes taken for assessment of gajrella were color, appearance, texture, flavor and overall acceptability.

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